Terahertz radar imaging for standoff personnel screening

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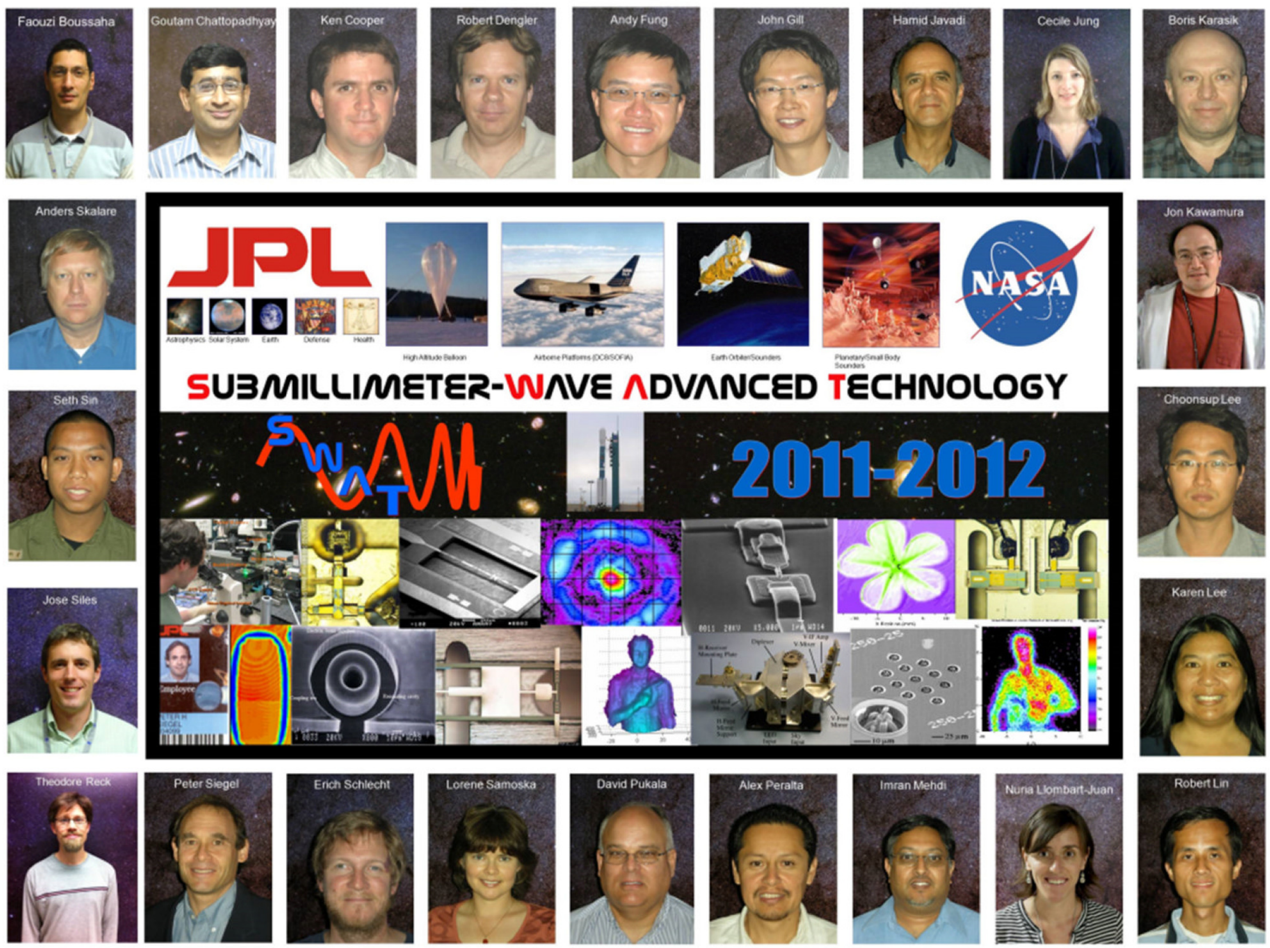
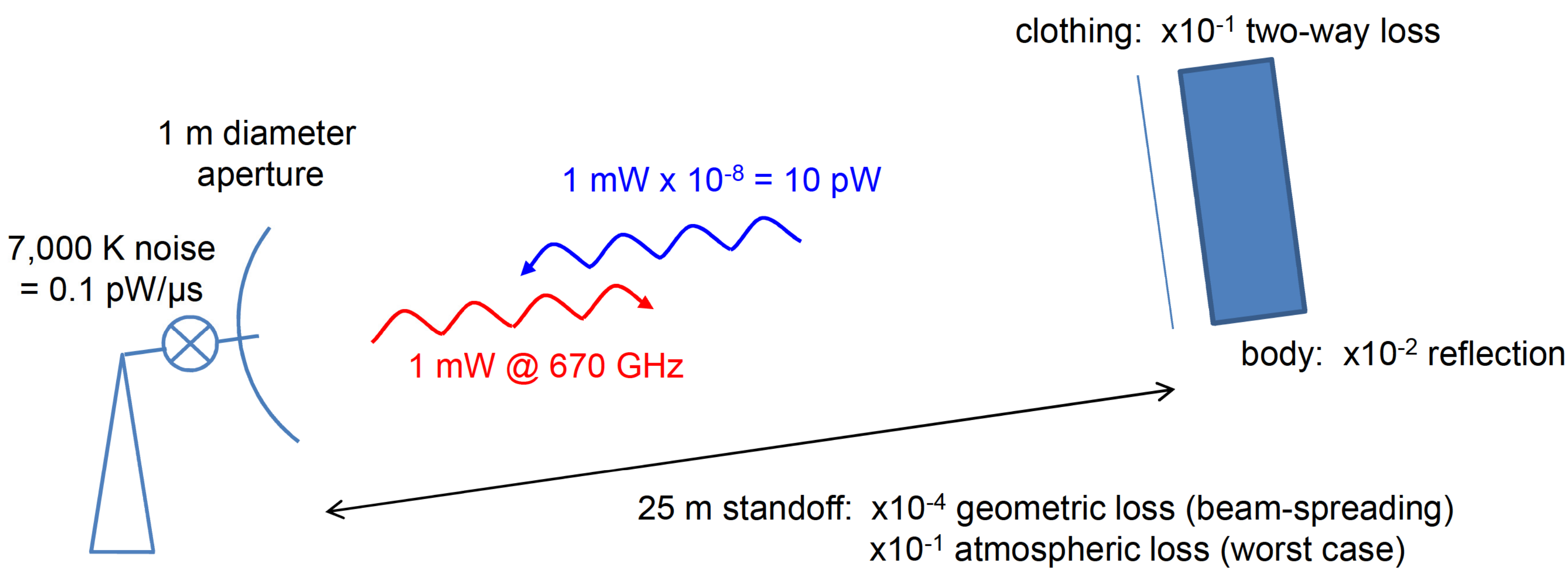


Active THz Imaging: SNR

Potential benefits of *active, narrowband* THz imaging:

- Very high SNR is possible because of **high-power sources and low-noise detectors**

- Video-rate imaging feasible with small number of transceivers



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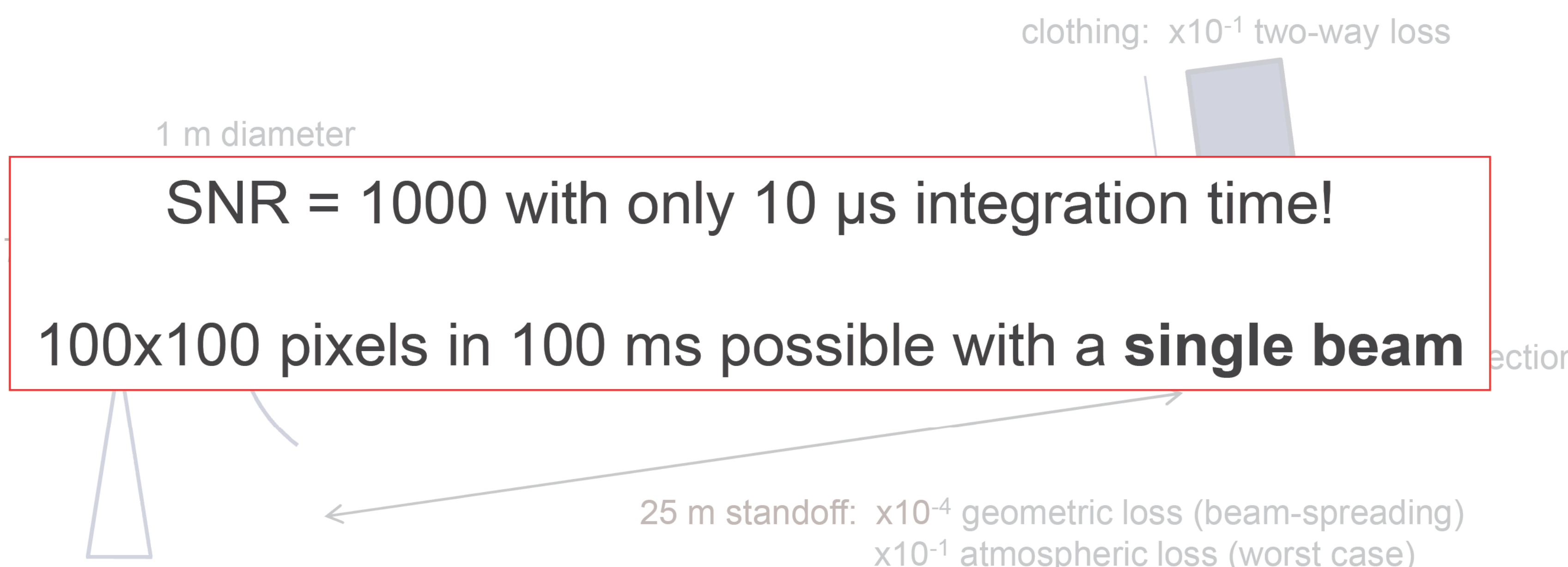
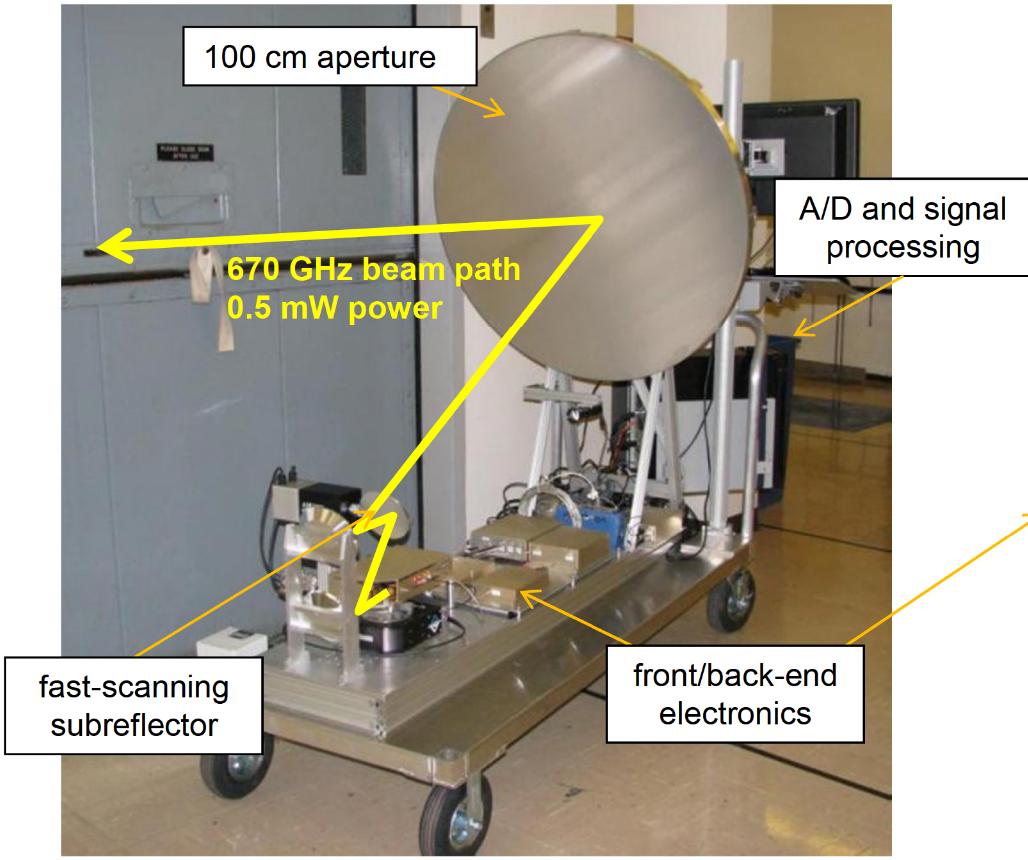
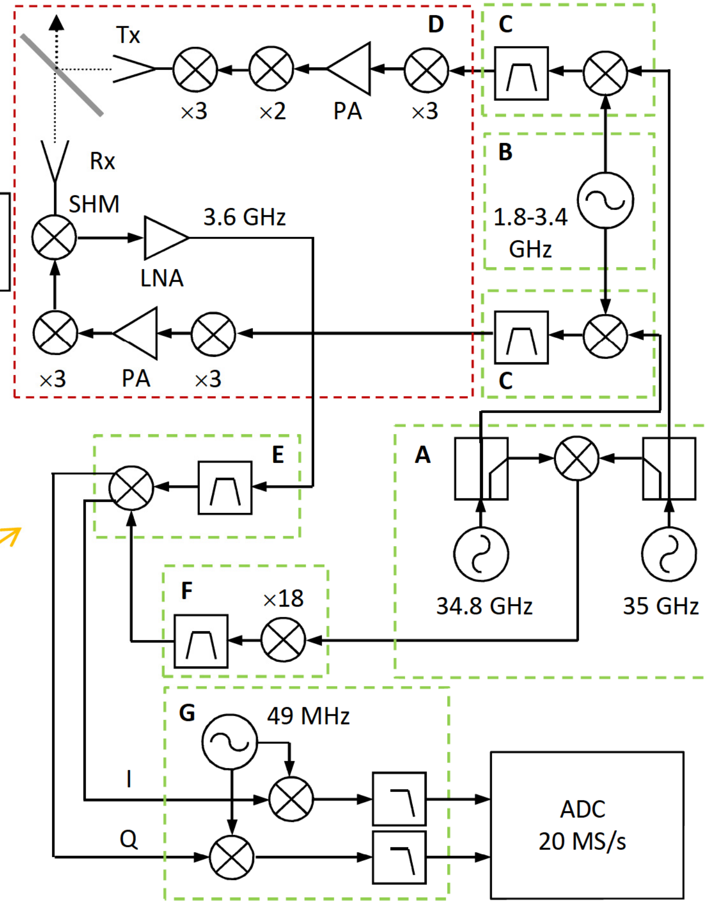


SNR = 1000 with only 10 μs integration time!

100x100 pixels in 100 ms possible with a **single beam**

JPL's THz Imaging System, 2011

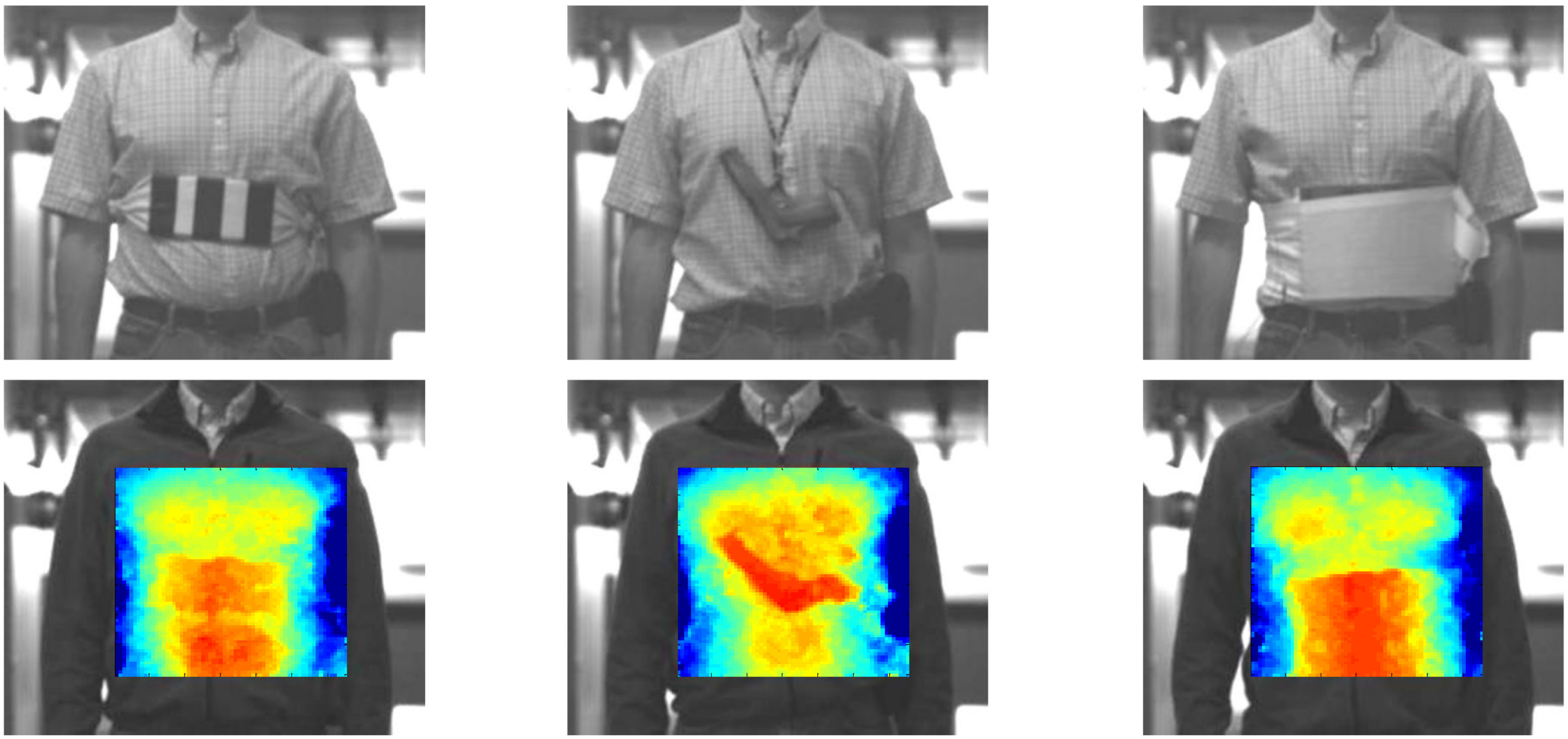




K.B. Cooper, et al., "THz Imaging Radar for Standoff Personnel Screening," IEEE THz Sci. & Tech., 2011.

Detection Image Gallery

small mock bomb belt (2.3 cm thick) | replica hand gun (2.5 cm thick) | large mock bomb belt (2.5 cm thick)



- Requirements for detection: solid object, ~1 inch in size (in 3 dimensions)
- Material of concealed object is irrelevant to detection

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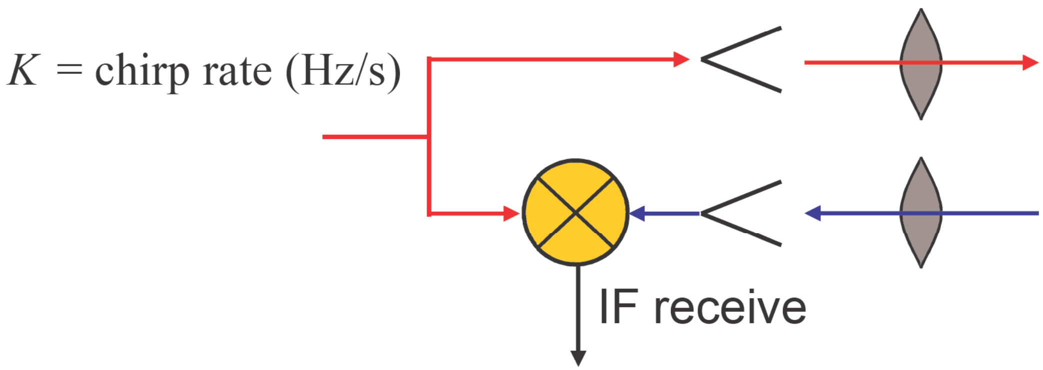
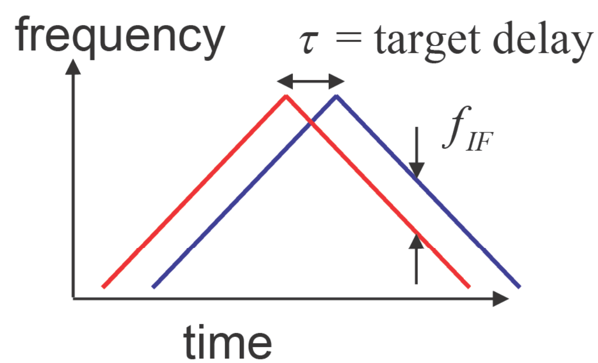
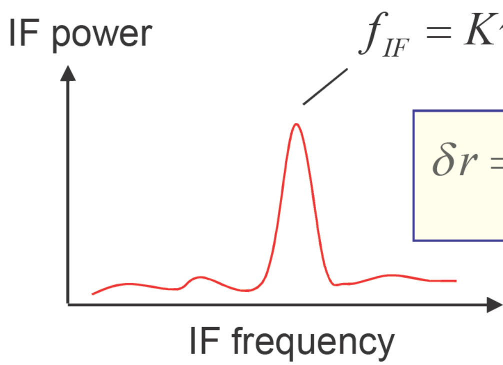
Frequency-modulated continuous wave (FMCW) radar:
appropriate when available power is limited.





Range resolution: inversely proportional to chirp bandwidth



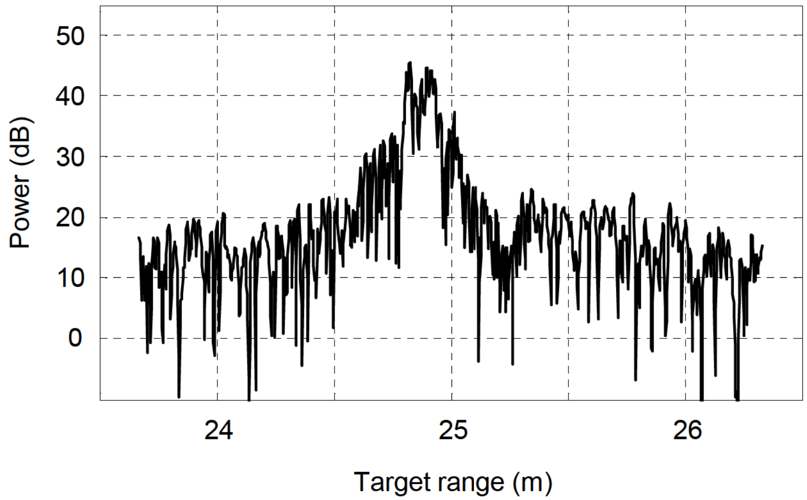
$$f_{IF} = K\tau = \frac{2KR}{c}$$

$$\delta r = \frac{c}{2\Delta F}$$

THz systems can achieve enormous bandwidths, and hence range resolution.

FMCW Waveform Nonlinearity

raw point-target range spectrum

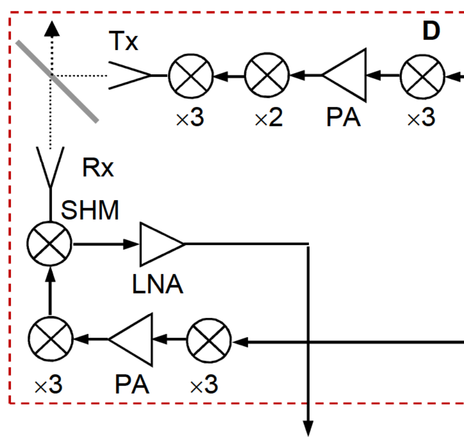


Range resolution from 28.8 GHz bandwidth

expected: <1 cm

achieved: ~25 cm

Broadening from modulation in amplitude and chirp profile causes modulation in IF signal. But if deterministic, then this can be "subtracted out"!



$s_T(t) = A_T(t) \cdot \exp[i\omega(t) + i\delta\Phi_T(t)]$

$s_{LO}(t) = A_{LO}(t) \cdot \exp[i\omega(t) + i\delta\Phi_{LO}(t)]$

$s_{IF}(t) = \exp(i\omega_R\, t) \cdot A_{IF}(t,R) \exp[2\pi i \cdot \delta\varphi_{IF}(t,R)]$

Nonlinearity Compensation

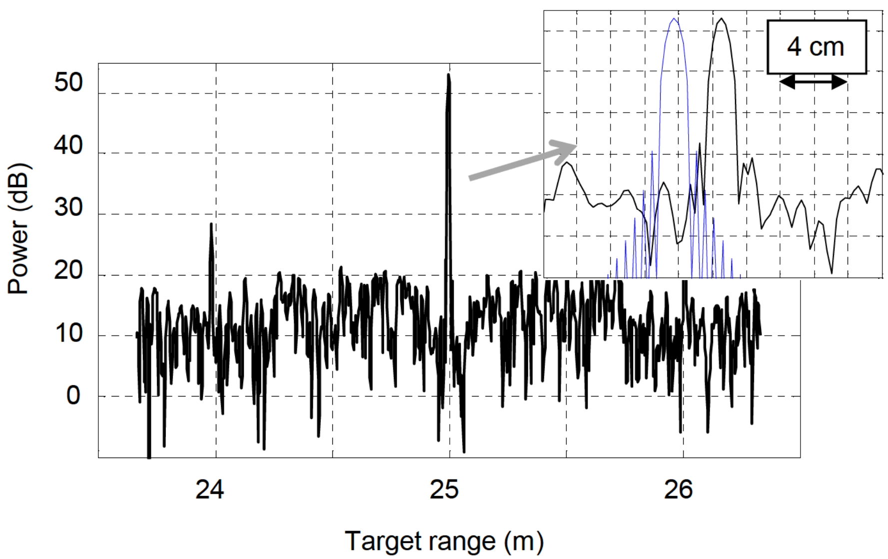
1. Acquire calibration waveform on point target:

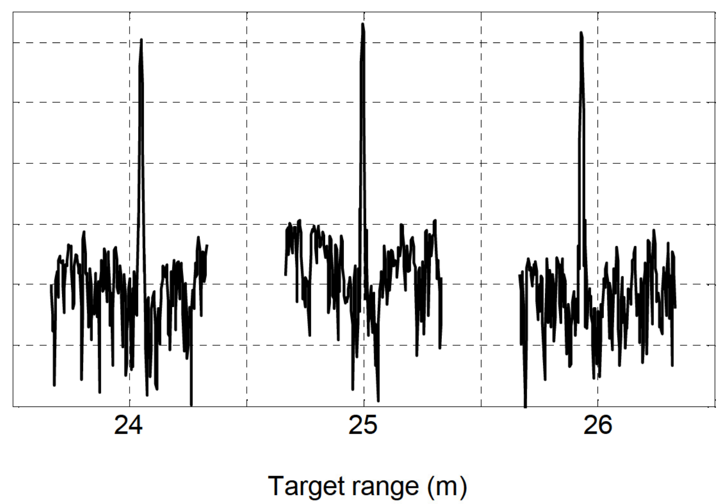
$$s_0(t) = \exp(i\omega_{R0}\, t) \cdot A_0(t,R) \exp[2\pi i \cdot \delta\varphi_0(t,R)]$$

2. Divide subsequent IF signals by (complex) calibration: bandwidth-limited resolution achieved

$$s_{IF}(t) \rightarrow s_{IF}(t) \div s_0(t)$$

$$\delta\varphi_{IF}(t,R) \rightarrow \delta\varphi_{IF}(t,R) - \delta\varphi_0(t,R_0) \qquad A_{IF}(t,R) \rightarrow \frac{A_{IF}(t,R)}{A_0(t,R_0)}$$



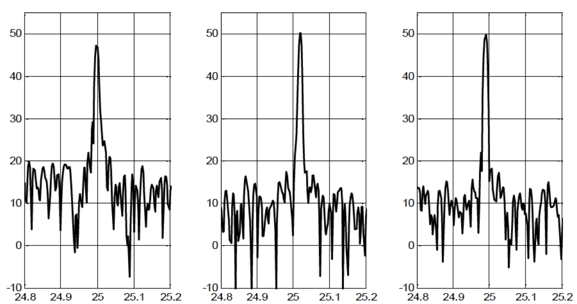


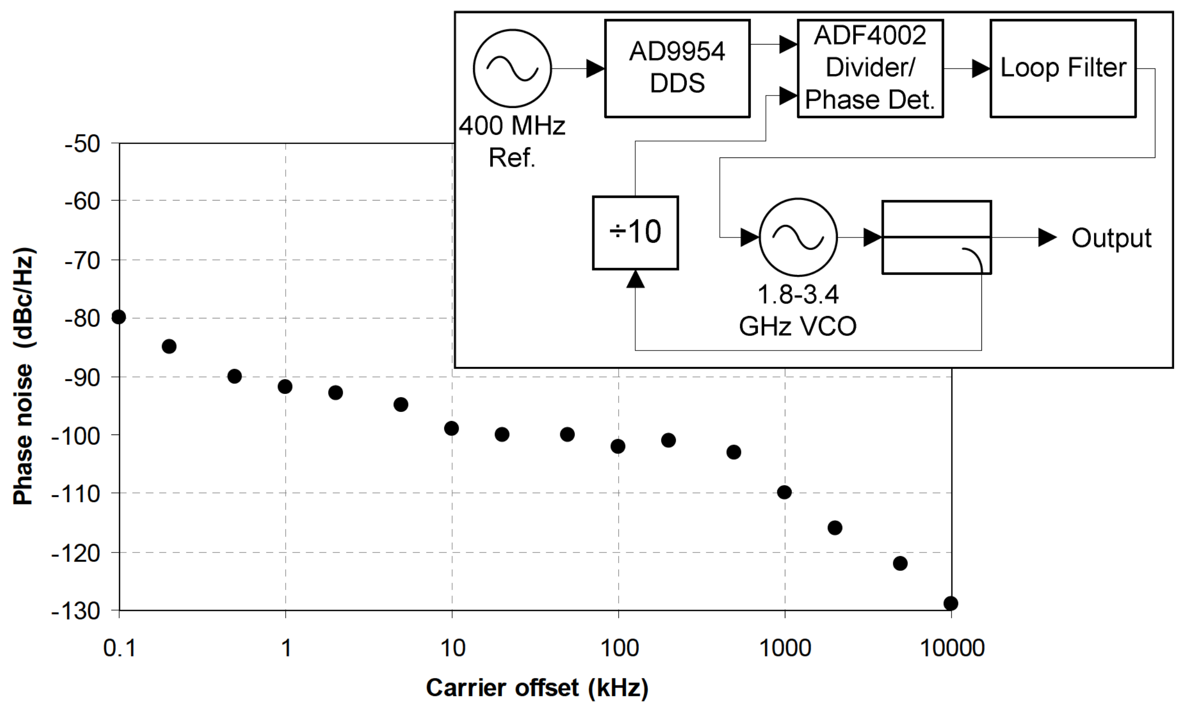
Achieving Stable, Fast, and Low-Noise Waveforms

<u>JPL built and designed chirper</u>

- 1.6-3.2 GHz up/down chirp in <0.1 ms
- Very low phase noise
- Digital synthesis stability
- Careful digital/analog ground isolation

DDS provides good range resolution stability:





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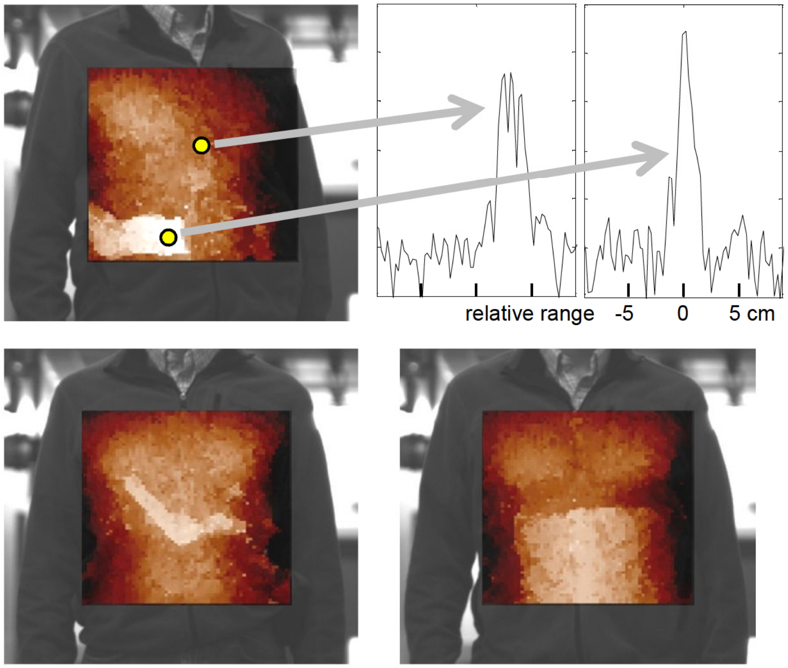
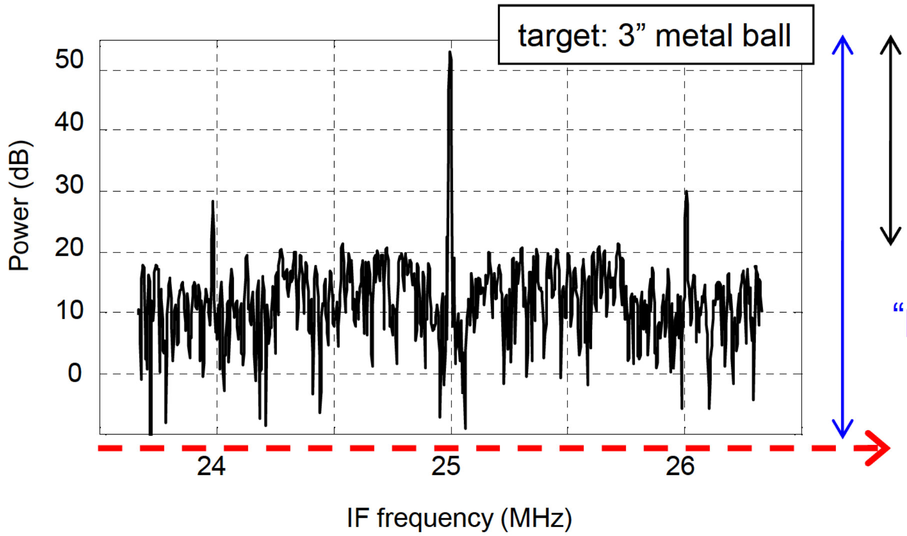
Imaging Algorithm: Surfaces of Last Scattering

High range resolution at cm-scale is critical for being able to digitally 'peel away' layers of clothing and reveal potential threats.



Phase Noise Limitations



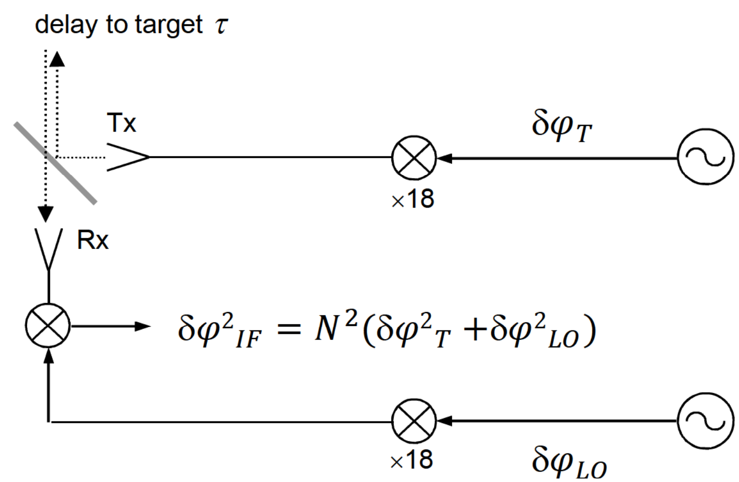
measured SNR: 34-44 dB (phase noise floor)

“potential” SNR: 67 dB (thermal noise floor)

thermal noise floor at -13 dB on this scale

Idealized phase noise model:

- Phase noise is multiplied in frequency multipliers
- For simple heterodyne measurement, transmit and LO phase noise is uncorrelated
- Expected phase-noise floor: -97 dBc/Hz + 3 dB 20log(18) dB + 10log(10kHz) dB = -29 dB
- We get -44 dBc above; *why so good? Can we do even better?*



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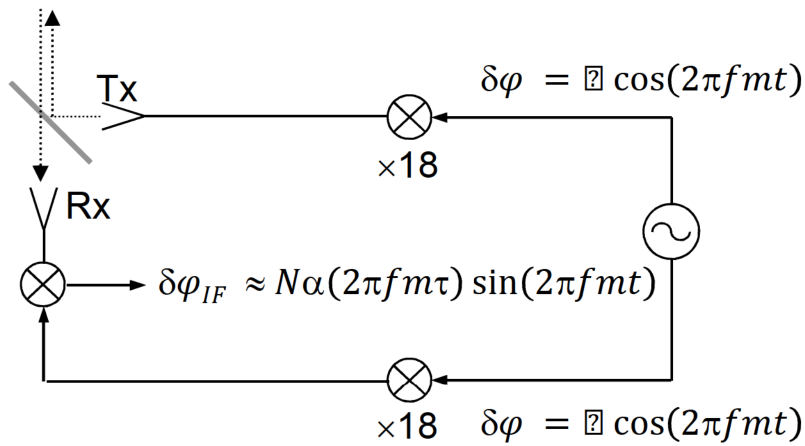
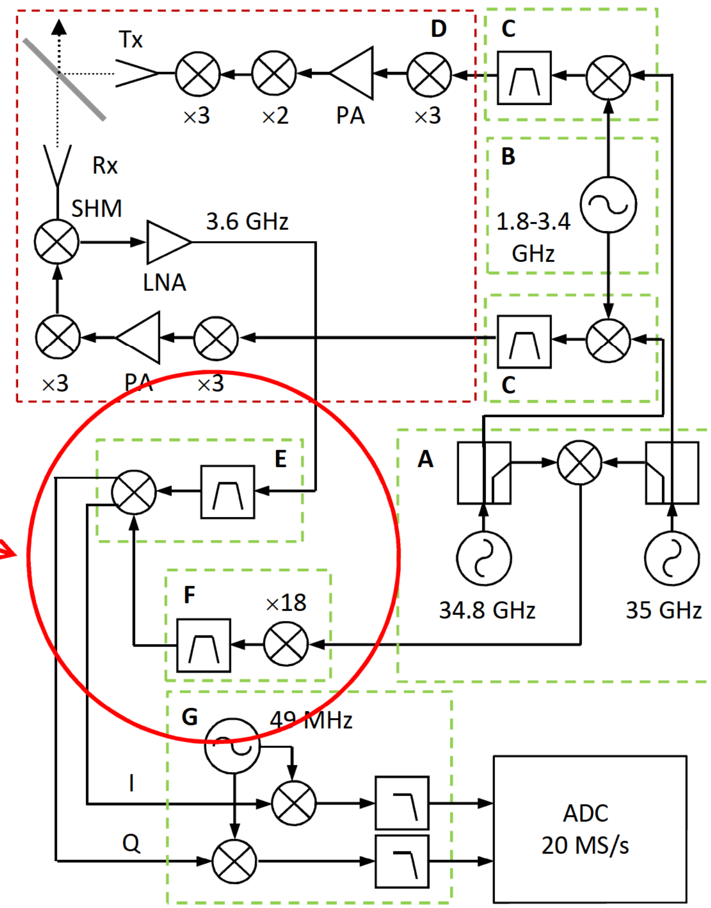
Phase Noise Cancellation via Homodyne

delay to target: τ



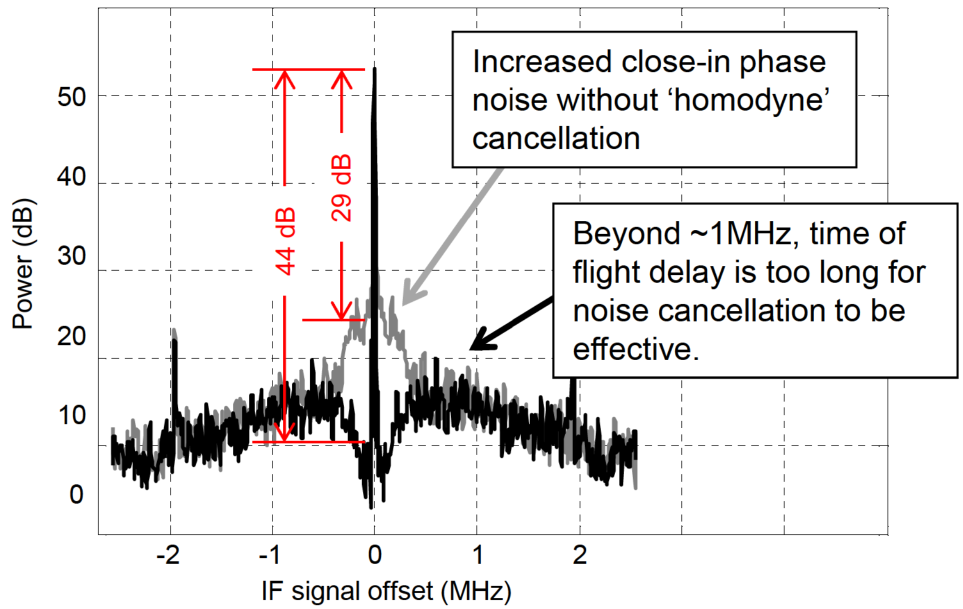


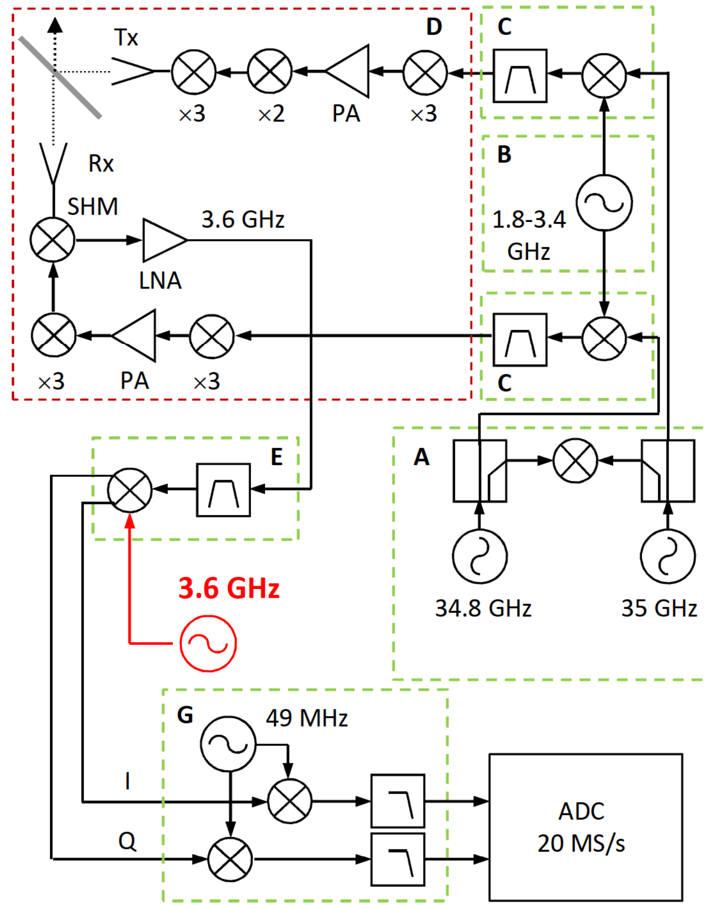
This makes the heterodyne effectively homodyne!

- Phase noise in IF will vanish if the electrical path delays are balanced
- One source of imbalance is the time-of-flight of $\tau \approx$ 170 ns = 6 MHz $^{-1}$
- At 100 kHz offset, expect cancellation of $(2\pi \cdot 100\text{kHz} \cdot 170\text{ ns})^2$ = -19 dB
- Expect -29 dBc -19 dB = -48 dBc phase noise floor; close agreement w/ msmt

J.L. Doane, "Broadband superheterodyne tracking circuits in millimeter-wave measurements," 1980.

Phase Noise without "Homodyne" Cancellation





Confirmation:

- -29 dBc noise floor restored without "homodyne" circuit in place.
- Complicated by chirp source common to Tx and LO chains, and by dispersion in submm electronics
- *Can tunable cancellation be improved?*

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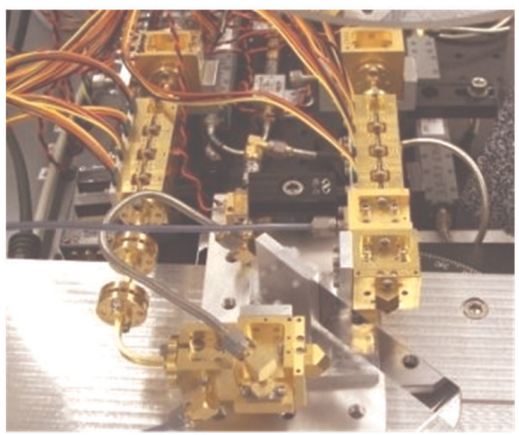
Goal: Near-Video Rate THz Radar Imaging

- Higher frame rates wanted: rapid crowd scanning, subjects in motion, wider field of view
- Better THz components will not help: bottleneck from mechanical scanning
- Path to video rates: scanning multiple beams simultaneously

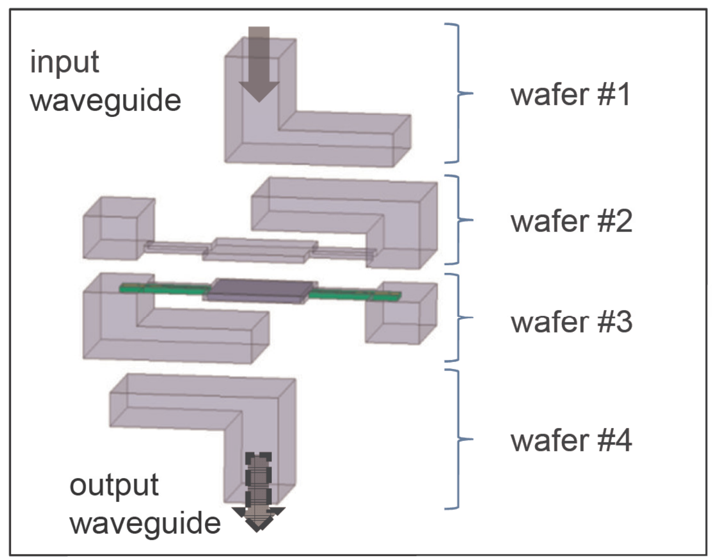
N beams = N x speed-up

But it's not practical to duplicate the front-end module 8 times!



~5 inches

Concept: 3D stacks of precision micromachined silicon waveguide: *extremely compact integration*



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Conclusions

- 670 GHz imaging radar is effective at detecting concealed threats
- Good penetration allows for covert operation and “seeing through” even thick clothing
- Chirp stability and calibration is critical for achieving high range resolution and hence high contrast imagery
- Careful circuit architecture can improve noise floor and dynamic range
- Transceiver array development is underway to reach near-video frame rates

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